per square yard; and 1.50 calories per minute, or 90 calories per hour, which is not an uncommon rate at midday in summer with a clear sky, represents over 1 kilowatt per square meter, or nearly 1.2 horsepower per square yard. The radiation received on a square meter of horizontal surface during a clear day in midsummer is equivalent to 5 kilowatt-hours; and a daily total per square centimeter of 600 calories, which is equalled or exceeded at Mount Weather on clear days from the middle of March to the end of August, is equivalent to 4 kilowatt-hours per square meter. The daily average at this season of the year, including all kinds of weather, is about two-thirds of that for clear weather.

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THE ABSORPTION OF THE ATMOSPHERE FOR ULTRA-VIOLET LIGHT.

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[Dated: Jefferson Physical Laboratory, Harvard University, Sept. 21, 1914.]

The absorption of the air, to which this article is devoted, manifests itself in two regions of the ultra-violet and is of particular interest to two classes of observers. The first region lies at the less refrangible end of the ultra-violet where glass is no longer transparent; the second region is the extreme ultra-violet where even quartz loses its transparency and where the ordinary photographic plate is no longer sensitive. It is the first region that is of interest to the meteorologist and to the student of cosmical phenomena, since it is here that atmospheric absorption influences the light we receive from celestial bodies. It is the second which is chiefly of importance to the pure physicist.

The absorption of the atmosphere in the first region finds its most striking illustration in the abrupt termination of the solar spectrum in the ultra-violet. If the light from the sun is examined by means of a quartz spectroscope, the spectrum is found to terminate rather abruptly near wave-length 3,000 Å. U.,[1] while if the spectrum of the iron spark or arc is examined, it is found to extend to near wave-length 2,000. That the difference in extent of the spectra from celestial and terrestrial sources depends on the difference in the thickness of the medium which produces the absorption is a fairly obvious hypothesis, but it was only after Cornu had put the matter to experimental test that the hypothesis was regarded as definitely established.

Cornu's first experiments consisted in observing the limit of the solar spectrum at different hours of the day. He observed that the position of this limit retreated toward the less refrangible region with decreasing altitude. He was able to express his results by means of the empirical formula—

$$\text{Sin } \theta = 0.49 \times \varepsilon^{-0.0833(\lambda-300)}$$

which exhibits the limiting wave-length λ in its relation to the sun's altitude θ. Now, as the altitude decreases, the sun's rays must pass through greater and greater thicknesses of the atmosphere; the observed phenomena, therefore, have been taken to prove that it is the atmosphere whose absorption determines the limit of the spectrum. In order to take the next step, however, and account for the exact form of the empirical expression, it is not only necessary to express the thickness of the absorption layer in terms of the sun's altitude, a thing which can be simply done if the layer is considered plane, but also the relation connecting the absorption coefficient of the absorbing gas with the wave-length must be known. This considerably extends the field of inquiry, for it becomes necessary to analyze the action of the atmosphere and determine which of its constituents are responsible for the observed effects.

A study of the subject has made it clear that it is sufficient to fix the attention upon oxygen and ozone since nitrogen and the other constituents do not appear to be major factors, at least in this region. Going a step farther, it seems that the part played by oxygen is interesting, and may be important, but as numerical data are lacking, it will be well to consider first the action of ozone for which the necessary figures are at hand.

Hartley(1) suggested some time ago that as ozone was known to possess a strong absorption band in that part of the ultra-violet where the sun's spectrum ends, the action of the atmosphere might be ascribed to the ozone which it contains. Recently, Fabry (2) and Buisson have measured the absorption coefficient α, as defined by the equation $I = I_o 10^{\alpha d}$, over the region between wave-lengths 3,500 and 2,200 and have applied their results to explain the form of the empirical relation of Cornu with which we are at present concerned. To this end they have plotted the logarithm of the absorption coefficient against the wave-length. The graph of this function is a straight line between wave-lengths 3,500 and 2,800. If this relation is combined with the expression connecting the thickness of the absorbing layer with the zenith distance, Fabry showed that an expression of the same form as the empirical equation of Cornu results. In fact, not only is the form the same but the numerical constants are nearly identical.

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[1] The Ångström unit of wave length is 10^{-10} meters and is usually abbreviated Å. U.—[C. A., jr.]

The net result of all this is that if we confine our attention to the relation connecting the thickness of the absorbing layer and the limit of the solar spectrum as found by Cornu at a single point on the earth's surface, the facts may be completely explained on the assumption that the active agent is the ozone in the earth's atmosphere. It is extremely important to observe that this conclusion does not depend on the distribution of the ozone in the atmosphere but only on the total amount of the gas between the observer and the sun. As we shall see presently we have reason to believe that the total amount as determined experimentally is sufficient to account for the facts.

The difficulties of the subject only become manifest when we attempt to follow Cornu in those experiments where he varied the thickness of the absorbing layer, not by observing the sun at various altitudes but by changing the altitude of the place of observation. In order to predict the manner in which the limit of the spectrum should vary with the altitude of the observer for constant altitude of the sun, it is obviously necessary to introduce a new hypothesis into the calculations. Cornu assumed that each cubic meter of the atmosphere contains the same per cent of the absorbing gas, and that the density of the atmosphere varies with the altitude according to the barometric law. He was thus led to a simple expression whose fundamental constant implicitly contained, among other factors, the relation between the absorption coefficient of the gas and the limiting wave length. The expression predicted that for every rise of 896 meters the spectrum should extend itself by 10 Ångström units.

By making observations with the sun at the zenith at various altitudes on the earth's surface, Cornu obtained values for the last visible wave length which were in fair agreement with those yielded by his formula.

These simple and satisfactory conclusions have recently been rather upset by the work of Miethe and Lehmann (3) and the observations of Wigand (4). The first mentioned observers found that if they concentrated their attention on the last trace of light action recorded on the photographic plate the position of this impression did not alter at all as the altitude was varied by 4,500 meters. Wigand extended the scope of the experiment by taking the spectroscope of Miethe and Lehmann to an altitude of 9,000 meters in a balloon. He found the position of the last trace of light action was the same at this great altitude as on the earth's surface at Halle. It occurred at wave length 2,897. These results appear to flatly contradict those of Cornu since they show that the limit of the solar spectrum is independent of the altitude of the observer. As a matter of fact, the conclusions of the German observers, though sufficiently perplexing, are not absolutely in contradiction with those of Cornu for Wigand and his countrymen actually measured the position of the last trace of photographic effect on the plate while Cornu's observations probably deal rather with the change in the intensity of the spectrum very near the limit; the imperfection of his apparatus did not permit him to detect the limit itself (4). It appears, therefore, that Cornu's experimental results are not to be discarded as wholly wrong; they represent part of the truth but not the whole truth. His simple formula, however, is obviously only an approximation of very limited range.

If the work of Miethe, Lehmann and Wigand is to be accepted, it is certainly impossible to ascribe the limit of the solar spectrum to the absorption of a gas uniformly distributed in the atmosphere. Now Cornu's data on the variation of the length of the solar spectrum at different times of day agree so well with Fabry's experiments on the absorption of ozone that one is loath to abandon the idea that this gas is an important factor in the phenomenon. One is naturally led to ask, therefore, if the gas can be distributed in the atmosphere in a manner which will account for the fact that the extreme limit of the spectrum is independent of the altitude of the observer while the distribution of intensity very near this limit varies with the altitude of the sun. In other words, have we any evidence to show that the concentration of ozone increases very rapidly in the atmosphere above 9,000 meters?

There are serious discrepancies among the results of various observers of the ozone content at moderate altitudes, and data as to the variation of the ozone content of the air over a considerable range of altitude are, as yet, rather meager. The results of Pring (5) are the most recent. He finds by experiments on the earth's surface that the ozone concentration of the air is 2.5×10^{-6} at 2,130 meters and 4.7×10^{-6} at 3,600 meters. The average of 10 sets of data obtained by sending up the apparatus in balloons to altitudes from 6 to 20 kilometers gave a value of 2.1×10^{-6} for the concentration. Furthermore, he calculates that if every cubic meter of air between the earth and the sun contained the same per cent of ozone which he finds experimentally at 3,600 meters, the gas layer would be equivalent to a thickness of pure ozone of 4.2 cm. at atmospheric pressure. Fabry has calculated from his observations that a layer of pure ozone 5 mm. thick would account for the limit of the spectrum as observed by Cornu at sea level. Pring's measurements, therefore, substantiate the claim of Fabry that ozone is the active agent in Cornu's results but they do not give evidence of the increased concentration in the upper atmosphere indicated by the observations of Wigand.

The whole question of the distribution of ozone at very high altitudes is still one worthy of the attention of experimenters. Pring's values for any one altitude were obtained by averaging data which vary over rather wide limits. His conclusions are of extreme importance, but it would be well to confirm them by a series of observations at some of the highest practicable points on the earth's surface.

The data at hand give us no right to assume that the absorption of ozone alone will account for the behavior of the atmosphere as indicated by the extent of the solar spectrum. Even the simplest phenomenon, however, is the result of a number of causes, so here the observed absorption is probably due to more than one agent. We have neglected the effect of nitrogen and of the impurities in the atmosphere such as carbon monoxide and water vapor, for such data as we have on the subject point to the fact that these agents are relatively unimportant in the particular part of the spectrum which we are studying. It must not be forgotten, however, that we know very little about the absorption of these substances in columns of the length which enter into the problem.

The action of oxygen is a matter which can not be neglected, but though its behavior in the extreme ultraviolet is pretty well understood, as we shall see presently, very little is really known about its behavior in the region where the solar spectrum ends. Liveing (6) and Dewar as long ago as 1888 tried to imitate the mass of oxygen which occurs in the atmosphere between the earth and the sun bycompressing the gas in a tube 18 meters long to a pressure of 90 atmospheres. Their results showed a stronger absorption of oxygen than would be required to account for the termination of the solar spectrum at wave-length 3,000; with the path length and pressure just mentioned the column of gas absorbed everything on the less refrangible side of wave-length 3,100. The observers were led to believe that their tube gave more absorption than the earth's atmosphere, for some of the bands in the less refrangible part of the spectrum were more intense in their experiment than when seen in the solar spectrum.

The accuracy of the imitation of the earth's atmosphere depends on the assumption that if the product of the pressure and path length of a gas remains constant the absorption of the gas remains constant; this hypothesis, known as Beer's Law, seems to hold for most gases throughout the visible part of the spectrum; it does not hold for gases in the infra-red. There seems some reason to believe from the work of Jannsen that it does not hold for part of the oxygen spectrum even in the visible. Be this as it may, it seems improbable that the departure from Beer's Law could do more than slightly modify the phenomenon observed by Liveing. It becomes evident, therefore, that the absorption of oxygen may be an important factor in the question under discussion. Unfortunately, no data exist for oxygen similar to that obtained by Fabry for ozone connecting the coefficient of absorption with the wave-length in the region of the ultra-violet. Until such evidence is forthcoming, the exact part played by oxygen in determining the limit of the solar spectrum will be unknown. We can say with some certainty, however, that as oxygen does not occur concentrated in the atmosphere at very high altitudes, it cannot be the cause of the phenomena observed by Wigand.

The treatment of the absorption of the atmosphere would not be complete without some mention of the part played by scattering. The predictions of Rayleigh and Schuster (7) have been admirably verified by Abbot (8), but the nature of the scattering action is such that it does not pretend to account for the abrupt termination of the solar spectrum near wave-length 3,000. The suggestion of Wigand that scattering at altitudes above 9,000 meters is an important factor does not seem tenable.

There is still one way of escape from the difficulty introduced by the observations of Miethe and of Wigand. If the sun itself sent out no light of a wave-length shorter than the limit obtained by these observers, the independence of this limit with altitude would be explained. That the sun's radiation terminates abruptly does not seem probable, but it may rapidly decrease in intensity with decreased wave-length in the ultra-violet. In this connection, data on the extent of stellar spectra would be of great interest. As far as I am aware, experiments of this type with quartz apparatus are still lacking. Moreover, experiments on the absorption of very long columns of air for light from a terrestrial source could not fail to give very important results.

I have treated the second region of ultra-violet absorption, mentioned at the beginning of this article, rather exhaustively in a forthcoming monograph in Sir J. J. Thomson's Series published by Longmans (9), so a very brief résumé will be sufficient here. The part of the spectrum in question lies on the more refrangible side of wave-length 1,900 and is known as the Schumann region. Here oxygen is the dominating factor; it begins to absorb strongly near wave-length 1,850. So intense is this action that a few millimeters of the gas completely cut out any light near wave-length 1,600. The gas partially regains its transparency near wave-length 1,300, but even here the light transmitted is very feeble. The present limit of the spectrum obtained from a concave diffraction grating lies near wave-length 900.

Very little is known of the absorption of oxygen between the region near wave-length 1,900 and the part of the spectrum where light from the sun ceases to reach us. The absorption observed by Liveing and Dewar may be the manifestation of the shoulder of the same absorption band which begins to rise so rapidly at the beginning of the Schumann region. On the other hand, oxygen may have two absorption bands in this region with a place of relative transparency between. If this second hypothesis is the correct one, it gives rise to a rather interesting speculation. For since ozone is known to regain its transparency near wave-length 2100 it is just possible that light from the sun of this latter wave length may reach us feebly, provided that the oxygen is sufficiently transparent at this point, and provided, also, that the sun gives out light of the required refrangibility. Meyer (10) looked for this "hole in the atmosphere" but he was unable to find it. However, since his experiments, the technique of observation has been considerably improved; it might be worth while to look again.

In conclusion, it is well to remember the debt we owe to the atmosphere as a protective agency. The bactericidal action of light is well known in the visible part of the spectrum, but the fact that this action suddenly increases many hundredfold at a given point in the ultra-violet is perhaps not quite so familiar. The following experiment performed by Prof. R. W. Wood, and which I have often seen repeated, illustrates this point. A glass plate coated with nutrient agar-agar is sprinkled with *Bacillus prodigeosus* and is exposed in a quartz spectroscope to the light from an iron spark. The plate is then removed and is maintained in a suitable moist atmosphere and at proper temperature. The growth of the bacillus is hardly affected by the light in the visible part of the spectrum but when a definite point in the ultra-violet is reached no growth occurs. The light has killed the bacillus. Now this point where the killing action becomes evident is the same for a great number of microscopic organisms and, what is most important, it lies but very slightly on the ultra-violet side of the point where the atmosphere cuts off the solar spectrum. As the abiotic action is by no means confined to pathogenic organisms, it is evident that the absorption of the air protects human beings from most unpleasant consequences.

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